Introduction to Multibunch Instabilities and Feedback

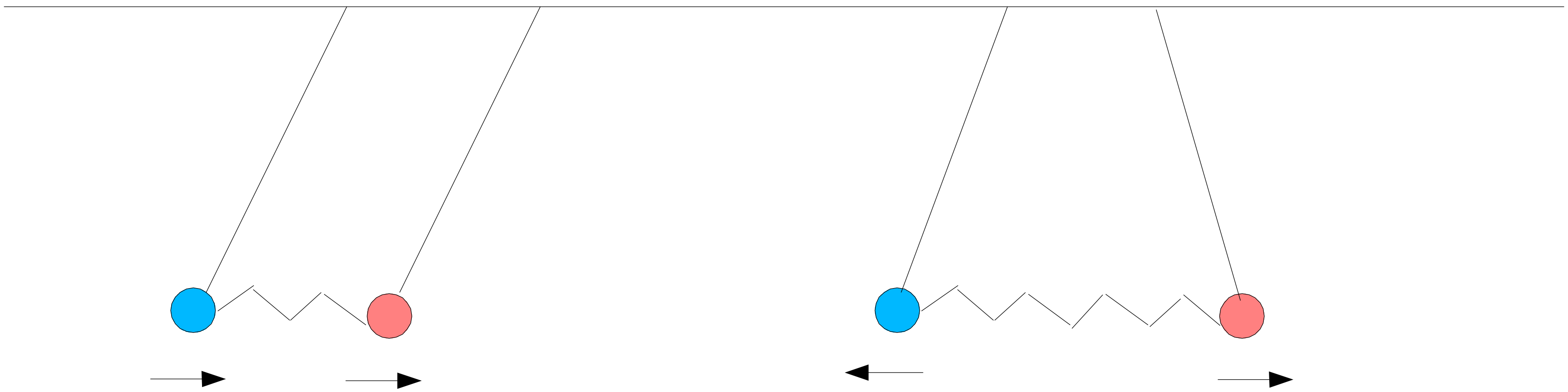
Nick Sereno

Friday June 20, 2003

Outline

- Coupled bunch mode physical analogy.
- Wakefields and impedances.
- Longitudinal and Transverse bunched beam modes.
- Landau Damping
- General feedback system considerations.
- Conclusion

Coupled Bunch Oscillations Physical Analogy



- Two coupled pendulums have two (eigen) modes of oscillation.
- The modes differ in frequency and phase.
- M degrees of freedom (bunches) have M oscillation modes.

Bunch to Bunch Coupling in Accelerators

- Bunches deposit EM energy in rf cavities and other accelerator structures as they move.
- The bunches can then couple to others through the EM energy they leave behind.
- Process described in terms of the wakefunction and its Fourier cousin impedance.
- The wakefunction W(t) is the impulse response of an accelerator structure to the passage of an impulse beam.
- Both transverse and longitudinal wakes.

Impedance

- Impedance is the fourier transform of the wakefunction.
- Convenient when describing beam instabilities in the frequency domain.
- Types
  - Narrowband: Cavity HOMs (long range, couples bunches to each other).
  - Broadband: Discontinuities, Resistive wall (short range, bunch distribution details are important).

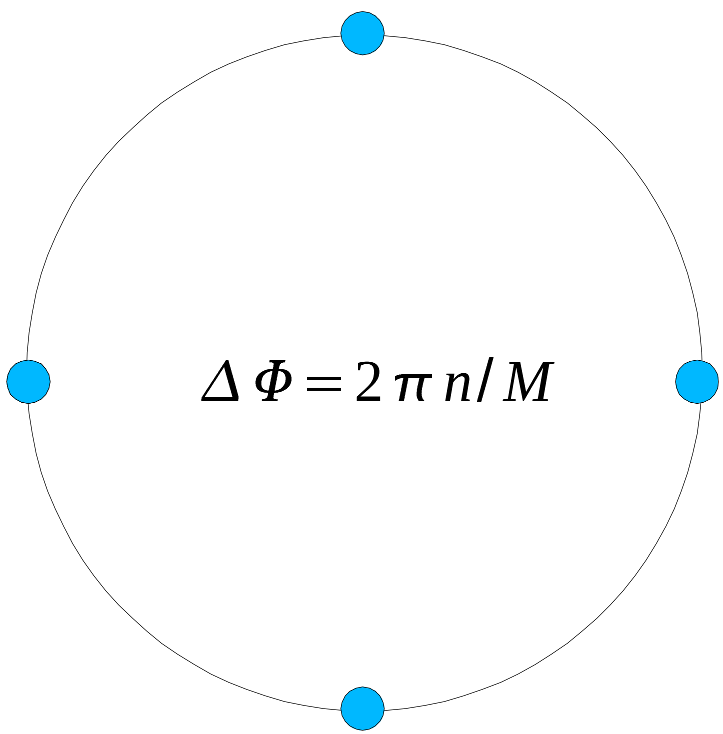
Types of Instabilities

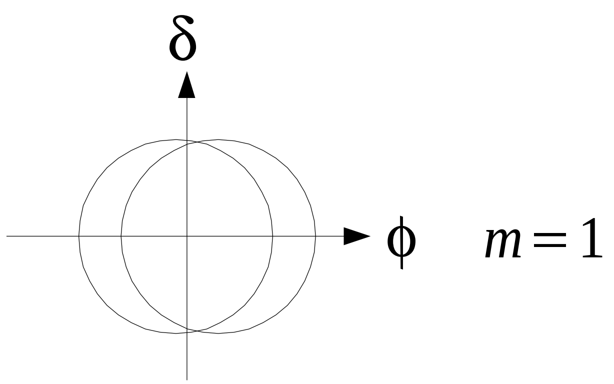
- Coupled Bunch Instabilities: Driven by narrowband impedances.
  - Long range wakefields.
  - Cavity HOMs (High Q).
  - Both longitudinal and transverse.
- Robinson Instability: Primarily driven by the fundamental rf mode.
  - Long range wakefields.
  - Other HOMs can drive this.
  - Longitudinal only.

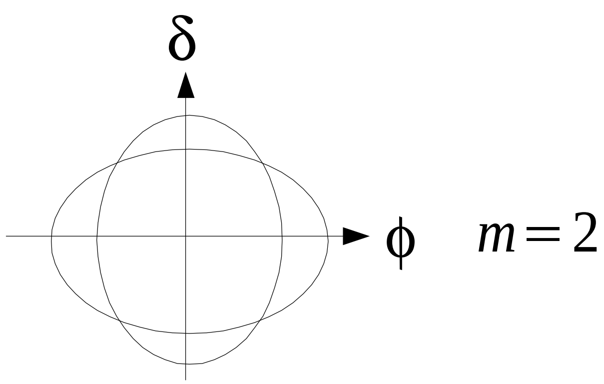
Types of Instabilities cont.

- Resistive Wall Instability: Driven by vacuum chamber surface resistivity.
  - Short perhaps to medium range wakefield.
  - Surface resistivity frequency dependence ~ $\omega^{(1/2)}$
  - Transverse only.
- Microwave, fast head-tail, transverse mode coupling instabilities: Driven by broadband impedances.
  - Short range wakefields.
  - Driven by discontinuities, steps
  - The detailed bunch distribution is important.

Longitudinal Coupled Bunch Modes







- Bunches M = 4 in this case, bunch to bunch phase shift δϕ for coupled bunch mode number n =0, 1, 2 3.
- Bunch phase space dipole and quadrupole modes. Denoted by m = 1, 2,... = number of periods of density modulation per synchrotron period.

Longitudinal CB Modes cont.

- Each mode has two lines within a band M times the revolution frequency.
- Each mode has many lines in the spectrum.

$$f_{nm,p} = (n + pM) f_{rev} + m f_s$$

- The mode number m longitudinal bunch density modulation in one synchrotron period.
- The envelope of the lines is related to the mode number m and the bunch length.

Longitudinal Growth Rate

- Complex frequency shift:

$$\Delta\omega_{m,n} \sim \omega_s \frac{I}{hV\cos\phi_s} \Sigma F_m(f_p\tau) \frac{Z_L(f_p)}{p}$$

- Frequency shift contribution to the impedance is weighted by the bunch form factor.
- Proportional to the total current.
- Growth rate of the mode is given by the imaginary part of the frequency shift.

Robinson Instability

- Interaction of the mode $n = 0$, $m = 1$, with the fundamental accelerating mode resonance.
- Potential instability if the fundamental mode resonance is below the revolution harmonic.
- Can be understood simply:
  - High energy particles in the bunch take longer to go around the ring (lower synchrotron frequency).
  - They sample higher values of the accelerating mode impedance and gain more energy.
  - Process repeats turn by turn.

Robinson Instability

- What to do to prevent this?
  - Adjust the cavity tuner to bring the cavity resonance above the revolution harmonic and sidebands.
  - Robinson damping is thereby achieved.
  - Damping process analysis is the same as instability.
- Cavity HOMs can sometimes induce the instability.
- Can also adjust the cavity tuner to change HOM resonances.
- Cavity temperature can also be used to tune HOM frequency.

Transverse Coupled Bunch Modes

- Now the spectrum has synchrotron sidebands around each betatron sideband.
- Now the mode number m represents the number of betatron wavelengths per synchrotron period.
- Mode number m can be negative (180 degree phase shift)
- What about the envelope of the spectrum?

Effect of Synchrotron Oscillations on the Transverse Modes

- Quadrupole focusing depends on energy.

$$\frac{1}{f} = kl = \frac{B'\,l}{B\rho}$$

- Particles undergoing synchrotron oscillations have a betatron tune modulation at ω_s.
- This adds a traveling wave component to the standing wave pattern given by m.
- Net effect for the transverse modes is that the envelope of the spectrum is shifted in frequency.

Instability Summary

- Can limit the current in high current machines such as light sources, B-factories.
- Instability when the growth rate of a particular mode or modes exceeds the damping rate.
- Fortunately for light sources, synchrotron radiation is a very effective damping mechanism.
- But, what are the options for eliminating the problem.

Options to Eliminate Multibunch Instabilities

- Synchrotron radiation damping.
- Landau damping (not very effective).
- Damp cavity HOMs as much as possible.
- Reduce vacuum chamber resistivity.
- Smooth vacuum chambers.
- Reduce the number of small gap chambers.
- Optimize RF cavity loops, temperature parameters.
- Multibunch feedback systems.

Digression on Landau Damping

- Applies to a collection of harmonic oscillators which have different oscillation frequencies.
- When each oscillator is driven by the same sinusoidal force, not all the oscillators are resonantly driven.
- Most oscillators eventually become out of phase with the driving force.
- Initial coherent motion of all the oscillators is damped.

Landau Damping cont.

- A multibunch instability can be damped by this mechanism.
- The energy put into the beam goes into increasing the beam size rather than centroid amplitude.
- Not very effective damping mechanism for modern light sources with small emittance and bunch length (small tune spread).

Feedback Systems

- Modern light sources require high beam currents.
- Growth rate of some trans/long modes exceeds radiation + landau damping.
- Feedback systems damp multibunch instabilities using pickups, processing electronics and kickers.
- But what is really going on?

Feedback Systems cont.

- The multibunch instabilities act like harmonic oscillators.
- The feedback system adds a damping term to the equation of motion of the bunch.

$$u'' + Du' + \omega_u^2 u = 0$$

- This is the equation of a damped harmonic oscillator.

Feedback Systems cont.

- Kicker is required supply a kick proportional to the angular position (x', y') for transverse feedback.
- Kicker supplies a kick in energy proportional to the energy offset relative to the synchronous energy for longitudinal feedback.

Feedback Algorithm

- Feedback algorithm to correct the instabilities can be summarized for longitudinal and transverse:
- 1: Measure the deviation of the bunch from the closed orbit.
- 2: Wait ¼ of a betatron or synchrotron period.
- 3: Apply a kick proportional to the measured displacement.

Feedback Systems cont.

- Must make a proper measurement of beam parameters in order for the feedback system to apply the correct kick with the correct sign.
- x', y' measurement:
  - Minimum 1 pickup a multiple of 90 degrees in phase advance apart from the kicker.
  - Better to use 2 bpms 90 degrees in phase apart to determine x', y' directly.
  - Longitudinal: Use a bpm/cavity sum signal to measure the arrival time of the beam.

Feedback System Gain

- In practice both longitudinal and transverse feedback systems supply up to a maximum kick.
- The maximum occurs at some maximum value of the detected longitudinal or transverse displacement.

$$Dl = \frac{\Delta u'_{max}}{u'_{max}} = G$$

Feedback System Gain cont.

- The damping time constant τ is related to the gain (in units of the revolution period):

$$\frac{1}{\tau} = \frac{Dl}{2T_o} = \frac{G}{2T_o}$$

- The equation represents the damping rate of the feedback system.
- This damping rate combined with radiation/landau damping must exceed the growth rate of the instability.

Feedback System Bandwidth

- Kicker BW: Extremes are a DC kick to all bunches up to ½ the bunching frequency.
- At a minimum system BW must be able to damp most unstable modes (largest growth rates).
- PEP II feedback system designed to damp all bunches (> 1000 bunches).

Effect of the Closed Orbit

- Processing electronics is required to eliminate the closed orbit or stable beam motion.
- Required to avoid system saturation.
- Longitudinal feedback systems typically require 70 dB suppression of the closed orbit signal.
- Transverse feedback requires around 50 dB.
- Bottom line is that after processing, the closed orbit signal sent to the kicker must end up much smaller than the betatron or synchrotron signals required for feedback.

Feedback System Classification

- Can have bunch by bunch feedback.
- Signal processing extracts the signal from each bunch.
- System applies a correction kick to each bunch.
- Can have mode by mode feedback where the system detects and processes coupled bunch mode sidebands.
- In mode by mode feedback, must choose which modes to detect and damp.

Summary

- Coupled bunch instabilities driven by the machine impedance from cavity HOMs discontinuities, vacuum chamber resistivity.
- Eventually, reducing the impedance is impractical (ie. HOM damping).
- At high beam currents both long/transverse instabilities may be present and require damping.
- Feedback system must be designed to damp all instabilities for a given maximum beam current and machine impedance.